Relationships Between Landscape Attributes and Landslide Frequencies After Logging: Skidegate Plateau, Queen Charlotte Islands

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Relationships Between Landscape Attributes and Landslide Frequencies After Logging: Skidegate Plateau, Queen Charlotte Islands

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ABSTRACT

Terrain within the Skidegate Plateau of the Queen Charlotte Islands was studied to determine if landslide frequencies could be correlated to specific landscape attributes or combinations of attributes. The analysis indicates that roadfill landslide frequency is associated with slope angle, natural landslide presence, slope position, and slope morphology, whereas clearcut landslide frequency is related to these factors as well as to surficial material, bedrock formation, horizontal slope curvature, and soil type. Combinations of these variables are used to develop landslide risk classifications.

Key Words: Landslide frequency, terrain, logging, road building.

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INTRODUCTION

The identification of terrain that will be subject to high frequencies of landslides following clearcut logging and road building is a high priority for forest management in coastal British Columbia, and the Queen Charlotte Islands in particular. This paper addresses post-logging landslide frequencies as they relate to individual landscape attributes and combinations of landscape attributes. The relationships described are directed toward the development of multifactor classifications for slope hazard mapping.

STUDY AREA

The study area comprises a series of selected clearcut areas within the Skidegate Plateau in the Queen Charlotte Islands. The Skidegate Plateau is a long, narrow, northwest-trending surface which separates the Queen Charlotte Ranges in the west from the Queen Charlotte Lowlands to the east (Figure 1). The plateau surface slopes gently towards the east. Although it is well dissected, it exhibits a topography composed of subdued, rounded hills and ridges separated by moderately wide, low-gradient valleys. Elevation of the plateau surface ranges from a few metres in the east to 750 metres in the west. Bedrock formations are composed primarily of volcanics, sediments, and metasediments; intrusive rocks are rare. The plateau was overridden by ice during the Pleistocene. As a consequence, all but the steepest slopes are dominated by morainal materials.

The Queen Charlotte Islands have a temperate coastal maritime climate. Mean monthly temperatures near sea level range from 1.2–3.6°C in January to 13.2–14.5°C in July. Seventy to 80% of the precipitation occurs between October and April; most of the high-intensity rainfall events occur during this period, frequently in October and November. Annual precipitation is highest on the west side of the Queen Charlotte Ranges (4500 mm), decreasing gradually across the Skidegate Plateau to the eastern edge of the Queen Charlotte Lowlands (1200 mm). Maximum rainfall intensities follow a similar pattern (Karanka 1986).

METHODOLOGY

The study was restricted to logged areas that were from 6 to 15 years old. The lower age limit was imposed to allow time for root strength to deteriorate and to provide a reasonable opportunity for large storms to act on the logged terrain. The upper age limit was set because well-advanced conifer regeneration often masks the presence of smaller landslides.

Clearcut areas of the appropriate age range were stratified by underlying bedrock formation and numbered in a systematic fashion. A subset of areas from each formation was then randomly selected for study.

For frequency estimation, landslides that could not be clearly distinguished on 1:20 000 scale aerial photography were excluded from the study. A landslide 0.05 ha in area can usually be identified at this scale of photography; landslides smaller than this were excluded even though they may have been visible in the field. Landslides identified in the field, which were 0.05 ha or larger and which apparently occurred after the photography, were included in the data set.

The terrain within each selected area was mapped at a scale of 1:20 000 according to a terrain classification system in common use in British Columbia (Ryder and Howes 1984). With this system, each map polygon is labelled with a series of codes describing the geologic materials, material textures, surface morphology, and any active or inactive geomorphic processes present. For efficiency, terrain units with slopes less than 15° were generally excluded from the study because they rarely show evidence of failure. Each terrain unit mapped was considered to be a single sample. As no two terrain mappers will produce identical maps, some unknown amount of bias will have been introduced by this procedure.

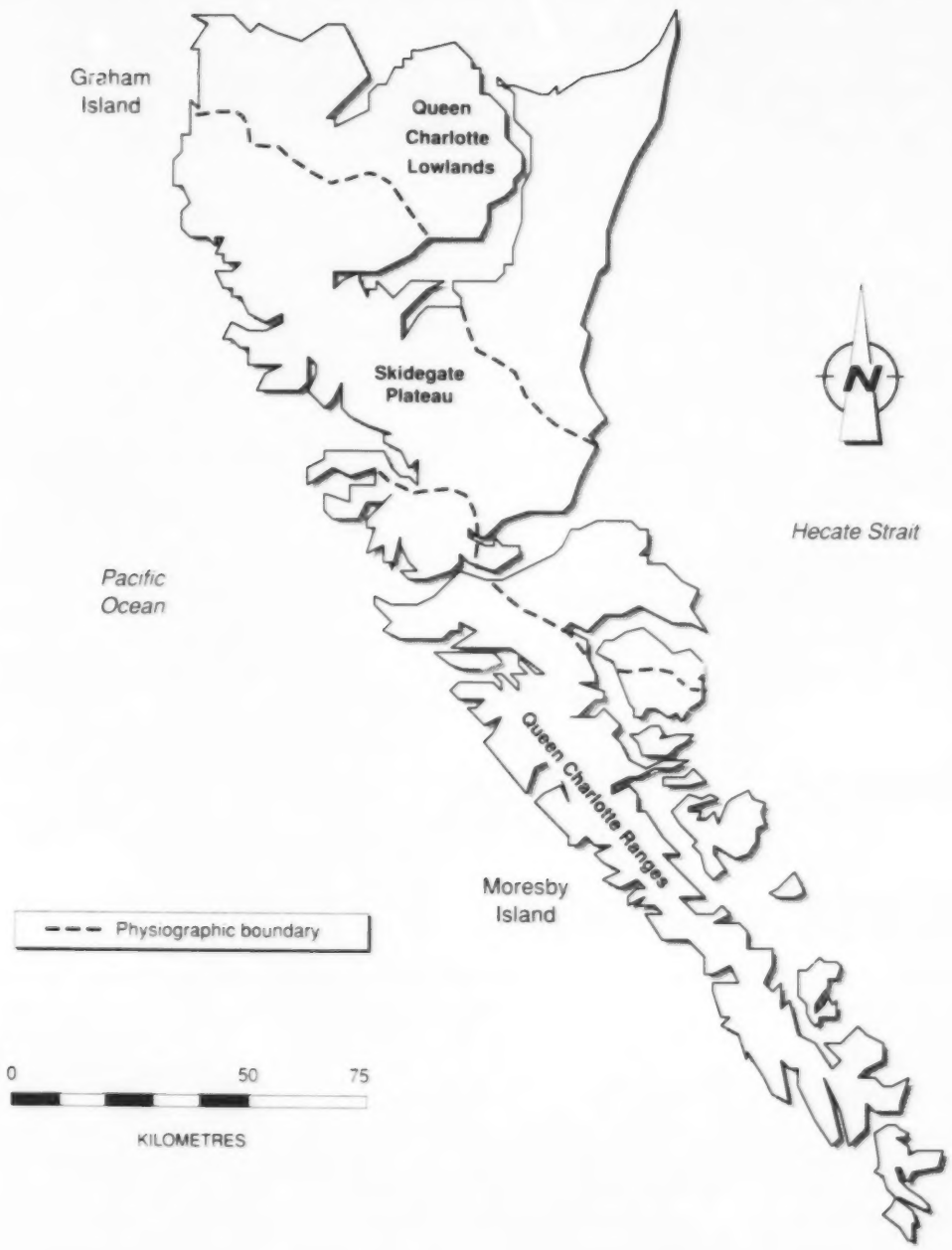

FIGURE 1. Physiographic regions of the Queen Charlotte Islands (from Sutherland-Brown 1968).

DATA COLLECTION

Twenty-eight randomly selected logged areas were studied (Figure 2), making up a total of 768 terrain polygons. The aggregate area mapped was approximately 3380 ha. Every terrain unit mapped was verified in the field, and a set of data describing the morphology and composition of the unit was recorded. The data included surficial materials present, slope angle, aspect, elevation, bedrock formation, soil type and texture, landscape position, drainage class, number of landslides, slope morphology, slope curvature along the horizontal, and the presence or absence of gullies.

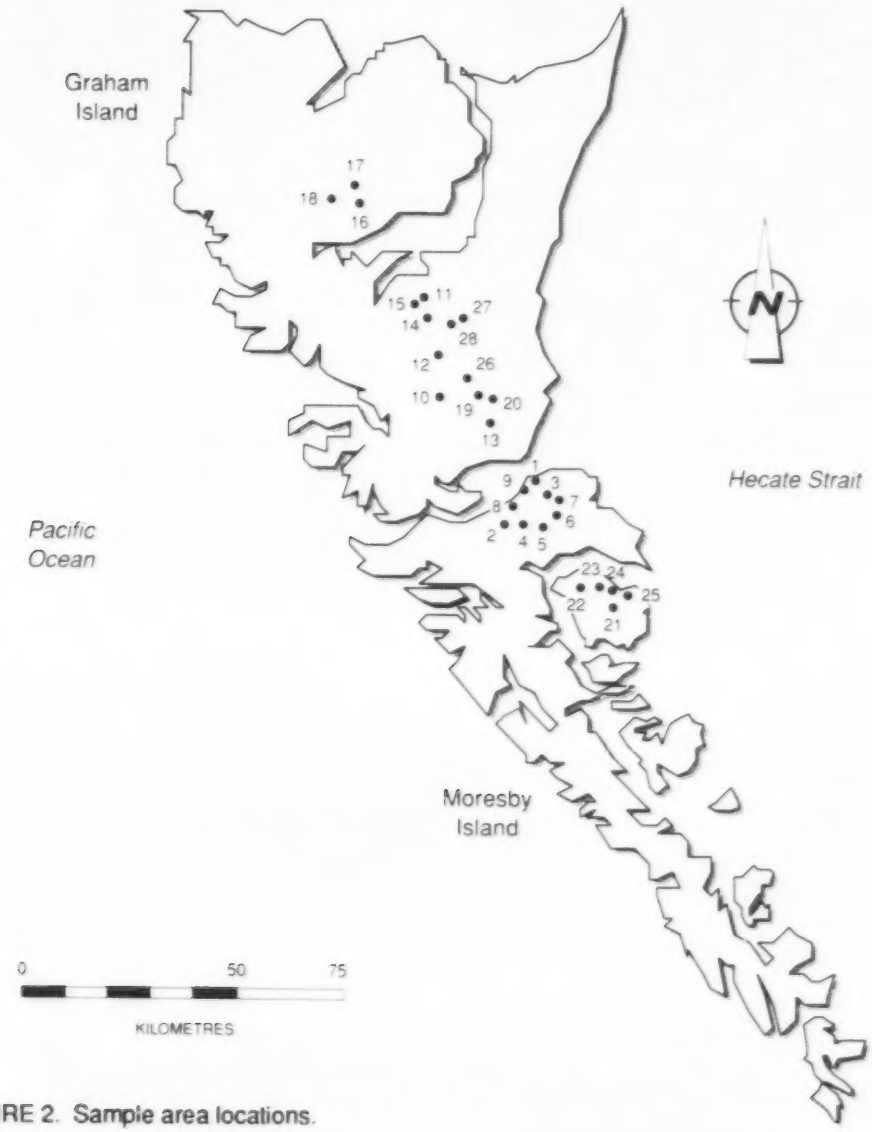

FIGURE 2. Sample area locations.

RESULTS AND DISCUSSION

As geographic variables are often not normally distributed, parametric tests were supplemented by nonparametric tests. Analysis of variance and the Kruskal-Wallis test were used to compare landslide frequencies with selected landscape attributes. In addition, multiple range tests were used to indicate groupings of attribute characteristics that are associated with similar landslide frequencies. Cross-tabulation and Chi-squared tests were used to compare landscape attributes with the presence or absence of post-logging landslides. The attributes compared include soil type, slope position, slope morphology, horizontal slope curvature, surficial material or terrain type, aspect, presence or absence of natural failures, soil moisture regime, and underlying bedrock formation. The development of a multifactor slope hazard classification using a series of variable combinations follows the approach of Rollerson and Sondheim (1985) and Howes (1987).

The most common types of landslides within the study area are clearcut and roadfill landslides, at 84.5 and 14.0% respectively. Roadcut landslides and landslides occurring at the clearcut boundaries are rare, accounting for only 1.3 and 0.2% of all landslides. Consequently, only clearcut and roadfill landslides were considered for further analysis.

Clearcut landslide frequency is expressed as the number of landslides per hectare. In the case of road failures, frequency is expressed on the basis of number of landslides per 100 m of road within each terrain unit.

Roadfill Landslides

A number of landscape attributes are related to roadfill landslide frequency in a statistically significant way (Table 1). For this analysis, the average slope angles for each terrain polygon were grouped into four slope classes (Table 2). These four classes show a clear trend of increasing landslide frequency with increasing slope angle. Because of the lack of roadfill failures on the most gentle slope class, the analysis then focused on polygons with average slopes greater than 20°. Roads located in terrain polygons that exhibit larger natural landslides (>500 m^2) are associated with relatively high failure frequencies, but this trend is less clear in those cases where minor natural landslides are present. Roadfill failure frequencies varied with landscape position.

TABLE 1. Comparison of landscape attributes and roadfill landslide frequencies

Variable[a]	Significance Levels[b]		
	ANOVA	Kruskal-Wallis	Chi-square[c]
Slope group	**	**	**
Presence or absence of natural landslides	**	**	**
Presence or absence of minor natural failures[d]	ns	**	**
Landscape position	**	**	**
Slope morphology	**	**	**
Dominant/subdominant terrain types	ns	*	**
Bedrock formation	ns	ns	ns
Horizontal slope curvature	ns	*	ns
Dominant soil type	ns	ns	ns
Soil drainage	ns	ns	ns
Slope aspect	ns	ns	ns

[a] All variables except slope group refer to areas with slope angles greater than 20°.
[b] Significance levels: ** = 0.01; * = 0.05; ns = not significant.
[c] Based on the presence or absence of post-logging landslide activity.
[d] Landslides with a surface area less than 500 m^2.

TABLE 2. Average roadfill landslide frequencies (failures per 100 m of road)

Variable[a]	Count	Average frequency	Percent failing units[b]	Homogeneous groups[c]
Slope group:				
0–20°	159	0.00	0	•
21–29°	110	0.09	7	• •
30–35°	104	0.13	20	•
36+°	32	0.24	25	•
Natural landslides (>500 m²):				
absent	234	0.10	13	•
present	12	0.56	50	•
Minor natural failures (<500 m²):				
absent	223	0.11	13	•
present	23	0.25	39	•
Landscape position:				
lower slope	27	0.02	7	•
upper slope	47	0.07	9	•
middle slope	140	0.16	14	•
headwater basin	27	0.27	37	• •
stream escarpment	5	0.68	40	•
Slope morphology:				
benchy	6	0.00	0	•
single gullies	14	0.00	0	•
uniform	168	0.10	12	• •
irregular	14	0.10	7	• • •
dissected	44	0.30	36	• •
Terrain types[d]:				
R/Cv	1	0.00	0	•
Mbv	124	0.06	8	•
CvR and/or MvR	16	0.16	19	•
Mbv and Cbav	65	0.18	25	•
Cbav	40	0.22	20	•
Bedrock formation:				
Honna	47	0.06	13	•
Haida	28	0.06	7	•
Longarm	16	0.11	19	•
Masset	82	0.12	12	•
Yakoun	37	0.13	19	•
Kunga	36	0.30	25	•
Horizontal curvature:				
convex	32	0.00	0	•
straight	136	0.13	15	•
concave	65	0.15	20	•
complex	13	0.26	23	•
Dominant soil type:				
podzolic	227	0.11	15	•
gleyed podzolic	19	0.21	21	•
Soil drainage:				
moderately well to imperfectly	91	0.08	11	•
well to moderately well	139	0.15	17	•
imperfectly to poorly	10	0.16	10	•
rapidly to well	6	0.19	33	•
Slope aspect:				
NE	35	0.07	14	•
NW	78	0.07	12	•
SW	60	0.17	13	•
SE	73	0.18	21	•

[a] Except for the variable slope group, all comparisons are for slope angles greater than 20°.
[b] Cross-tabulation analysis showing the percentage of units with one or more landslides.
[c] Multiple range analysis, by the method of 95% confidence intervals. Vertical columns indicate variables that are not significantly different.
[d] R/Cv = bedrock dominant over colluvial veneers.
Mbv = morainal blankets (>1 m deep) and veneers.
CvR = colluvial veneers and bedrock in equal proportions.
MvR = morainal veneers and bedrock in equal proportions.
Cbav = colluvial blankets, aprons and veneers as homogeneous units or complexes.

The highest roadfill landslide frequencies were associated with first-order (headwater) drainage basins and stream escarpments. Slope morphology shows some relationship to landslide frequency: the highest frequencies are found in those terrain units dissected by several gullies. Larger individual gullies (large enough to map as individual units) and benchy areas experienced no roadfill failures. No significant differences were detected with differing terrain or surficial material types, bedrock formations, slope curvature, soil type, soil drainage, or slope aspect. In some cases weak but logical trends were evident in the data.

Of note is the correspondence between roadfill landslide frequencies and the percentage of units within a specific variable group that experience roadfill landslide activity (Table 2). Groups that experience a high percentage of failing units also exhibit higher landslide frequencies. For purposes of ranking for hazard or risk, either statistic would seem suitable.

Clearcut Landslides

Clearcut landslide frequencies show statistically significant relationships with a greater number of landscape attributes than do roadfill failures (Tables 3 and 4). As with roadfill failures, frequency increases generally correspond to an increase in the percentage of units within a given class that experience failure. The percentage of units within a group experiencing failure can be taken as an indication of the future likelihood, or probability, of failure following logging on similar terrain (Rollerson and Sondheim 1985).

Groupings of average slope angles show a trend of increasing landslide frequency with increasing slope angle. Both large and minor natural landslides show a positive relationship to clearcut failure frequencies. The highest post-logging landslide frequencies recorded are associated with those terrain polygons containing natural failures. As with road failures, first-order headwater basins and stream escarpments are associated with high clearcut landslide frequencies. Terrain polygons dissected by gullies again show higher landslide frequencies than any other slope form; benchy and irregular slopes have very low landslide frequencies.

Some clear differences are evident between different terrain or surficial material categories. In part, the differences in failure frequencies between surficial material categories are thought to be a function of slope steepness. For example, deep morainal materials that have relatively low failure frequencies are typically found on gentler slopes than colluvial materials that show higher failure frequencies.

TABLE 3. Comparison of landscape attributes with clearcut landslide frequency

Variable[a]	Significance Level[b]		
	ANOVA	Kruskal-Wallis	Chi-square[c]
Slope group	**	**	**
Presence or absence of natural landslides	**	**	**
Presence or absence of minor natural failures	**	**	**
Landscape position	**	**	**
Slope morphology	**	**	**
Dominant/subdominant terrain types	**	**	**
Bedrock formation	**	**	**
Horizontal slope curvature	**	**	**
Dominant soil type	**	*	ns
Soil drainage	*	ns	ns
Slope aspect	ns	ns	ns

[a] All variables except slope group refer to areas with slope angles greater than 20°.
[b] Significance levels: ** = 0.01; * = 0.05; ns = not significant.
[c] Based on the presence or absence of post-logging landslide activity.

TABLE 4. Average clearcut landslide frequencies (failures per hectare)

Variable[a]	Count	Average frequency	Percent failing units[b]	Homogeneous groups[c]
Slope group:				
0–20°	258	0.03	7	•
21–29°	205	0.14	24	•
30–35°	223	0.28	34	•
36+°	74	0.38	34	•
Natural landslides (>500 m²):				
absent	737	0.15	20	•
present	23	0.74	87	•
Minor natural failures (<500 m²):				
absent	715	0.14	20	•
present	45	0.59	58	•
Landscape position:				
apex (ridge)	10	0.00	0	•
lower slope	111	0.06	13	•
upper slope	157	0.13	19	•
middle slope	417	0.15	21	•
headwater basin	50	0.56	64	•
stream escarpment	15	0.67	53	•
Slope morphology:				
irregular	46	0.02	7	•
benchy	27	0.04	7	•
uniform	550	0.12	19	•
faceted	9	0.18	22	• •
single gullies	44	0.29	25	• •
dissected	84	0.51	57	•
Terrain types[d]:				
R/Cv	6	0.02	17	•
Mbv	454	0.11	17	• •
Cbva	90	0.16	20	• • •
CvR and/or MvR	51	0.28	28	• • •
Mbv and/or Cbav	159	0.31	37	• •
Bedrock formation:				
Longarm	27	0.05	26	•
Masset	223	0.08	16	• •
Yakoun	145	0.14	17	• •
Haida	65	0.15	23	• • •
Honna	137	0.18	29	• • •
Kunga	163	0.33	29	• •
Horizontal curvature:				
complex	44	0.09	16	•
convex	110	0.11	18	• •
straight	436	0.14	18	• •
concave	170	0.30	37	• •
Dominant soil type:				
podzolic	460	0.21	29	•
gleyed podzolic	42	0.51	43	•
Soil drainage:				
moderately well to imperfectly	164	0.21	31	• •
well to moderately well	282	0.22	28	• •
rapidly to well	23	0.31	26	• • •
imperfectly to poorly	32	0.54	50	• •
Slope aspect:				
NE	69	0.17	15	•
SW	110	0.22	26	•
SE	149	0.25	23	•
NW	174	0.26	23	•

[a] Except for the variable slope group, all comparisons are for slope angles greater than 20°.
[b] Cross-tabulation analysis showing the percentage of units with one or more landslides.
[c] Multiple range analysis, by the method of 95% confidence intervals. Vertical columns indicate variables that are not significantly different.
[d] R/Cv = bedrock dominant over colluvial veneers.
Mbv = morainal blankets (>1 m deep) and veneers.
CvR = colluvial veneers and bedrock in equal proportions.
MvR = morainal veneers and bedrock in equal proportions.
Cbav = colluvial blankets, aprons and veneers as homogeneous units or complexes.

There are also significant differences among different bedrock formations. The Kunga formation, formed in large part of thinly bedded argillites and minor limestones, has the highest failure frequencies. The Longarm formation (sandstones) and the Masset (basaltic and rhyolitic volcanics) have the lowest failure frequencies. The Yakoun (andesitic volcanics and other minor volcanic rocks), Haida (sandstones, siltstones and shales), and the Honna (conglomerates and minor sandstones) formations hold an intermediate position.

Evaluations of slope curvature along the horizontal plane show concave slopes (often the first-order headwater basins noted above) to have twice to three times as many failures as other forms. Imperfectly drained soils tend to have higher failure frequencies than other types on slopes steeper than 20°, although the relationship is not significant when all slope categories are considered. Slope aspect did not prove to be a significant factor affecting landslide frequency in clearcut areas.

Multifactor Landslide Risk Classification

Two multifactor landslide risk classifications were developed from the results of the single attribute analysis: one for roadfill failures and one for clearcut failures (Tables 5 and 7). Typically, the attributes used in such classifications are those that have a statistically significant relationship to post-logging landslide frequencies. In this case, we also selected for those morphological attributes (e.g., slope angle, landscape position, slope morphology) that would be most tractable for automated map generation from digital terrain models and for features easily identified on aerial photography (e.g., natural landslide scars, gullies, stream escarpments). Such an approach allows for development of slope hazard maps in areas where soils or terrain maps are lacking or are very general. The aim of this exercise is to try to develop classifications that separate the landscape into units with either high or low landslide frequencies (Tables 6 and 8), although invariably some units or classes exhibit moderate landslide intensities. A comparison of Tables 7 and 8 with Tables 2 and 4 suggests that we were able to achieve a greater degree of separation than was possible using the single factor approach. The lack of well-defined homogeneous groups indicates that the class structure represents a continuum rather than a series of discrete groups. Further separations could have been made, for instance, had bedrock type or surficial materials been used to subdivide some classes. At some point, however, small sample sizes preclude further subdivision.

TABLE 5. Multifactor landslide risk classification for roadfill landslide occurrence

Class	Slope range	Natural landslides	Landscape position	Slope morphology
A	≤20°	Absent	Any	Any
B	21–29°	Absent	Any	Benchy, irregular, single, large gullies
C	21–29°	Absent	Lower, mid- and upper slopes, headwater basins and stream escarpments	Uniform
D	21–29°	May be present	Lower, mid- and upper slopes, headwater basins and stream escarpments	Dissected and/or natural landslides present
E	30–35°	Present	Any	Any
F	30–35°	Absent	Headwater basin	Uniform
G	30–35°	Absent	Headwater basin	Dissected
H	30–35°	Absent	Mid- and upper slopes	Uniform, faceted
I	30–35°	Absent	Mid- and upper slopes	Dissected
J	30–35°	Absent	1. Lower slopes and stream escarpments 2. Mid- and upper slopes	Any Irregular, benchy, single, large gullies
K	≥36°	Absent	Any	Any
L	≥36°	Present	Any	Dissected
M	≥36°	Present	Any	Uniform, faceted or irregular
N	≥36°	Present	Any	Single large gullies

TABLE 6. Multifactor landslide risk classification for roadfill landslides, significance values, and landslide frequencies (failures per 100 m of road)

Class	Count	Average frequency	Percent failing units	Homogeneous groups[a]
A	159	0.00	0	•
B	7	0.00	0	• •
J	26	0.00	0	• •
N	3	0.00	0	• • •
I	8	0.07	25	• • •
C	92	0.08	7	• • • •
H	51	0.10	18	• • • •
G	11	0.19	36	• • • • •
M	19	0.20	21	• • • • •
L	5	0.26	40	• • • • • •
D	11	0.27	27	• • • • • • •
F	3	0.30	67	• • • • • • • •
K	5	0.51	40	• • • • • •
E	5	0.74	60	• •

Test	Significance levels
ANOVA	0.01
Kruskal-Wallis	0.01
Chi-square	0.01

[a] Vertical columns indicate classes which are not significantly different.

TABLE 7. Multifactor landslide risk classification for clearcut landslide occurrence

Class	Slope range	Natural landslides	Landscape position	Slope morphology
a	≤20°	Absent	All	All except gullied
b	≤20°	Absent	All	Dissected
c	All	Present	All	All
d	21–29°	Absent	Headwater basins and stream escarpments	Dissected
e	21–29°	Absent	Headwater basins and stream escarpments	Other
f	21–29°	Absent	Upper, mid- and lower slopes	Dissected
g	21–29°	Absent	Upper, mid- and lower slopes	Other
h	30–35°	Absent	Headwater basins and stream escarpments	Dissected and/or imperfectly drained
i	30–35°	Absent	Headwater basins and stream escarpments	Other
j	30–35°	Absent	Upper, mid- and lower slopes	Dissected and/or imperfectly drained
k	30–35°	Absent	Upper, mid- and lower slopes	Other
l	≥36°	Absent	Headwater basins and stream escarpments	Uniform or dissected
m	≥36°	Absent	Headwater basins and stream escarpments	Other
n	≥36°	Absent	Upper, mid- and lower slopes	Uniform or dissected
o	≥36°	Absent	Upper, mid- and lower slopes	Other

TABLE 8. Multifactor landslide risk classification for clearcut landslides, significance values, and landslide frequencies (failures per hectare)

Class	Count	Average frequency	Percent failing units	Homogeneous groups[a]
a	244	0.02	5	•
g	172	0.07	16	•
o	26	0.09	15	• •
f	11	0.11	46	• • •
k	172	0.23	28	• • •
i	10	0.24	30	• • • • •
j	18	0.28	39	• • • • • • •
b	13	0.30	31	• • • • • • • •
n	32	0.38	34	• • • • • • •
h	20	0.59	75	• • • • • •
e	2	0.67	100	• • • • • • • • •
c	24	0.72	88	• • •
d	7	0.81	71	• • • •
l	5	0.88	40	• • • •
m	4	1.15	50	•

Test	Significance levels
ANOVA	0.01
Kruskal-Wallis	0.01
Chi-square	0.01

[a] Vertical columns indicate classes which are not significantly different.

CONCLUSIONS

The study results indicate that certain landscape attributes correspond clearly with landslide frequency and likelihood of occurrence (percentage of units experiencing failure). These include landscape position, slope angle, slope morphology, and the presence or absence of natural landslides. These results can be used to develop predictive landslide risk maps. Such maps can present landslide risk as the expected frequency of failure per unit area or as a simple likelihood of occurrence. The general lack of clearly defined homogeneous groups (see Tables 2, 4, 6 and 8), both for individual attributes and the multifactor classes, suggests that site-specific application of these results should be done with caution.

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